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14. ABSTRACT
As a contribution to the Marginal Ice Zone DRI, this research element was designed to observe the seasonal evolution of the upper-ocean stratification, document the time-varying ocean currents and characterize the turbulent ice-ocean exchanges of heat, salt and momentum as the sea ice cover retreats poleward in spring/summer using Ice-Tethered Profilers with Velocity. A total of 5 systems were deployed for MIZ, programmed to acquire vertical profiles of upper-ocean temperature, salinity and horizontal velocity at 3 hour resolution, as well as direct vertical turbulent flux estimates from just below the ice-ocean interface several times per day. Results advance understanding of the Arctic air-ice-ocean system.

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Autonomous Observations of the Upper Ocean Stratification and Velocity Fields About the Seasonally-Retreating Marginal Ice Zone

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Long Term Goals

The PI group seeks to build understanding of the physical processes controlling the Arctic's evolving air-ice-ocean system in support of efforts to predict its future state. A secondary goal is to develop and perfect autonomous instrument systems to observe the upper Arctic Ocean.

Objectives

As a contribution to the Marginal Ice Zone DRI, this research element was designed to observe the seasonal evolution of the upper-ocean stratification, document the time-varying ocean currents and characterize the turbulent ice-ocean exchanges of heat, salt and momentum as the sea ice cover retreats poleward in spring/summer. Observations and insights deriving from the MIZ program advance understanding of ice-ocean interactions and their parameterizations in numerical models. The primary instrumentation used in this study was the Ice-Tethered Profiler with Velocity (ITP-V). A technical goal of this project was to improve the velocity measurement system of the ITP-V.

Approach

The specific approach of this element of the MIZ DRI involved deployment of Ice-Tethered Profilers with Velocity (ITP-V) to sample the ocean and return those observations to the PIs in near-real time. A total of 5 systems were deployed for MIZ, programmed to acquire vertical profiles of upper-ocean temperature, salinity and horizontal velocity at 3-hour resolution, as well as direct vertical turbulent flux estimates from just below the ice-ocean interface several times per day. The ITP-V is a variant of the ITP system that has contributed to sustained observations of the Arctic Ocean below sea ice since 2004. The ITP-V instruments add a multi-axis acoustic-travel-time current meter and associated attitude/motion measuring unit to the standard ITP sensor suite to make direct, 3-D observations of ocean flow (Figure 1).

Tasks Completed

In preparation for the main field program, the PI's constructed and fielded one ITP-V in conjunction with the 2013 cruise of the Beaufort Gyre Observing System program (see http://www.whoi.edu/beaufortgyre) to test improvements made to the initial prototypes of the ITP-V instrument. For the main MIZ field program that began in Spring 2014, 3 ITP-V systems were deployed in an approximate north-south line spanning the seasonal sweep of the MIZ. Fellow MIZ investigators fielded complementary sensor systems in conjunction with the ITP-Vs. The Spring ice camp work was followed by summer cruises to deploy drifting and mobile instruments to sample the ocean around the spring MIZ assets. In conjunction with that latter effort, a 5th ITP-V was deployed during the August cruise of *MV Araon*.

The ITP-V instruments operated until May 2015; the dataset is complete and has been finalized. From the 5 ITP-V systems deployed in the program, Figure 2, a total of 8,888 profiles and 3,840 fixed depth records were obtained over a total of 1,150 instrument-days of sampling. Temperature, salinity and absolute ocean velocity profiles were obtained from 6 m below the ice-ocean interface to 250 m depth at 3 hr interval (with on average, one profile per day to 750 m). The fixed depth records were collected a few meters beneath the ice-ocean interface and used to estimate the vertical turbulent fluxes of heat, salt, and momentum. Hourly GPS fixes tracked the motion of the supporting ice floes and T/C recorders sampled the ocean waters just below the ice-ocean interface at 15-minute interval. Data processing has been completed following procedures detailed by Krishfield et al. (2008) for the CTD and Cole et al. (2014; 2015) for the velocity sensor. These products have been made available to fellow MIZ investigators. The MIZ ITP-Vs sampled in a range of ice conditions from full ice cover to nearly open water and observed a variety of stratification and ocean velocity signals (e.g., changes in mixed layer properties, internal wave energy levels, eddies).

Results

An undergraduate student from VIT University in India, Ratnaksha Lele, conducted a WHOI Summer Student Fellow Program investigation into sea ice dynamics and energetics using MIZ data under the supervision of Toole and Cole (Lele, 2015; Lele et al., 2016). Terms in the momentum and kinetic energy equations for ice floes were evaluated (apart from internal ice stresses that were derived as residuals) and the dominant balances assessed. On subinertial timescale, the dominant balances appear to be between wind work driving ice motion and ice-ocean drag damping those motions, Figure 3. At higher frequency, significant near-inertial variability was observed, particularly in summer when the ice concentration was reduced. Lele presented his research at the 2016 Ocean Sciences meeting.

Yale graduate student Mengnan Zhao working with Timmermans took the lead analyzing mesoscale eddies across the full Arctic including the MIZ ITP-V measurements. This comprehensive analysis indicated that a particularly energetic mesoscale eddy field was in place during the MIZ experiment (Figure 4). Zhao took the lead writing this work up for journal publication (Zhao et al., 2016).

Cole led the investigation into the ocean velocity and stratification variability observed by MIZ ITP-Vs. On short time scales, marked responses to individual storm wind events were observed, Figure 5. A synthesis and analysis of ice and upper-ocean velocity revealed spatial and seasonal variations in ice-ocean coupling (e.g., ice-ocean drag coefficients), in part attributable to differences in the initial multi-year ice floe sizes surrounding the instruments. A parallel analysis of the internal wave field below the surface layer showed that internal wave shear increased significantly with modest amounts of open water (~70% ice concentration). Smoother ice was associated with less internal wave generation and increased internal wave reflection (Figure 6). Independent of changes in the mixed layer depth, the dominant vertical wavelength shifted towards smaller scales as ice concentration changed from greater than 95% to 70-95%. This work was reported at the 2016 Ocean Sciences meeting (Cole and Toole, 2016); two peer-reviewed papers are poised for submission (Cole et al., 2017a,b).

In collaboration with Naval Postgraduate School doctoral candidate Shawn Gallaher (and his supervisors), the collective MIZ observations were used to quantify the evolution of the ice-ocean boundary layer in response to seasonal thermal forcing. The study identified a series of phases in the boundary layer evolution through summer, highlighting in particular the role of melt pond drainage on the upper ocean stratification and ice-ocean interaction, Figure 7 (Gallaher et al., 2016ab).

MIZ ITP-V measurements were used in a MIZ DRI model-observation synthesis to investigate Beaufort Gyre dynamics and thermodynamics in recent decades (Zhang et al., 2016). Collective MIZ observations and a coupled ice-ocean model (the Marginal Ice Zone Modeling and Assimilation System, MIZMAS) were employed to corroborate that the Beaufort Gyre circulation has intensified over the past two decades, with a stabilization of the spin-up after 2008; these changes are predominantly a result of the basin-scale wind forcing.

The PI's of this project continue to collaborate with fellow MIZ investigators in the analysis of the extensive dataset gathered during the MIZ field program. Several additional publications beyond those noted above are expected in early 2017.

Impact for Science

The peer-reviewed scientific papers and meeting presentations based on the Marginal Ice Zone program constitute a major contribution to our understanding of the "new" Arctic Ocean with its much thinner and more mobile ice cover. Beyond the research contributions, one new WHOI Assistant Scientist (Cole) and an engineer with limited PI experience (Thwaites) participated in the MIZ ITP-V project as co-principal investigators. Both have led or contributed to presentations and peer-reviewed papers based on the MIZ program. In addition, a WHOI Summer Student Fellow (Lele) based his project on MIZ data. This individual is presently enrolled in graduate school at the Scripps Institution of Oceanography. Also, ITP-V investigators have collaborated with a Naval Postgraduate School student (Gallaher) whose dissertation is based on MIZ observations. After graduation, this person will assume a teaching position at the Naval Academy.

Relationships to Other Programs

The ITP-V MIZ project segued directly into the present Stratified Ocean Dynamics of the Arctic (SODA) DRI program. The MIZ project also has connections to the Arctic Observing Network initiative by the National Science Foundation (specifically the Ice-Tethered Profiler activity and Beaufort Gyre Observing System).

Figures

Figure 1. a. Schematic drawing of the Ice-Tethered Profiler instrument system. b. Engineering drawing of the Ice-Tethered profiler with Velocity. c. Photograph of an MIZ ITP-V being deployed in the MIZ project (top) and in a test jig used to used to calibrate the Attitude, Heading Reference System (bottom).

a.

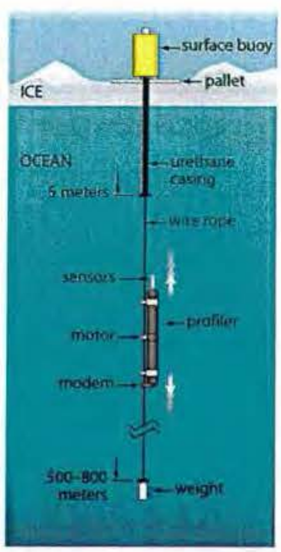

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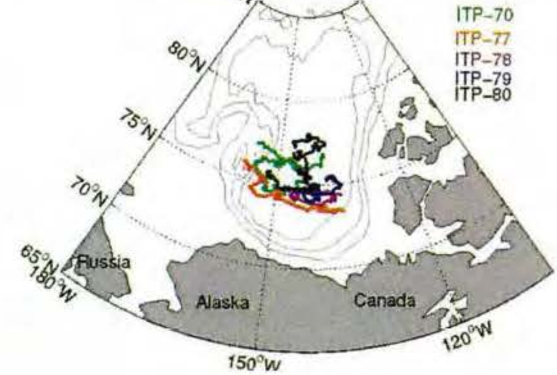
Figure 2. Drift tracks of the 5 ITP-V systems deployed during the Marginal Ice Zone DRI program.



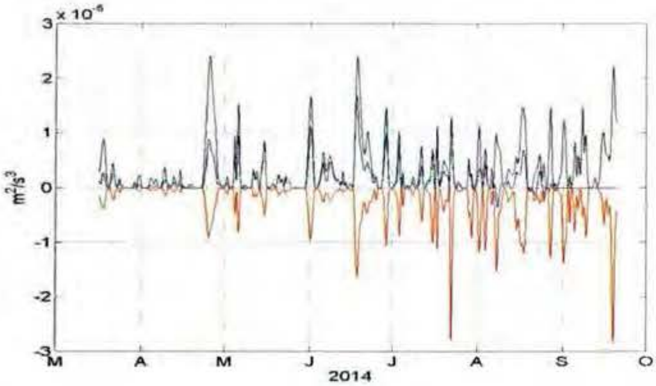


Figure 3. Time series of the wind stress work (blue and black) and the ocean stress work (red) on one of the MIZ sea ice floes that supported a buoy cluster. The two wind work estimates derive from directly-measured winds (blue) and the ERA-I model product (black). The ocean stress was derived from a quadratic drag formula with drag coefficient taken from direct turbulent momentum flux estimate. From Lele, 2016.

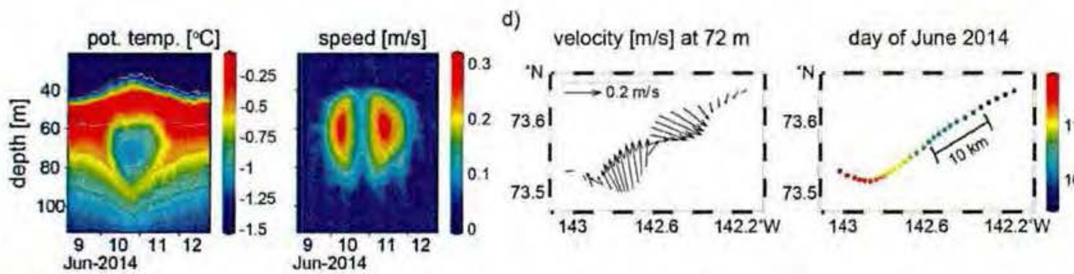


Figure 4. Observations of a typical halocline eddy sampled by an MIZ ITP-V instrument. First panel: potential temperature (°C)-depth (m) section overlaid with salinity contours; second and third panels: velocity magnitude (m/s)-depth (m) section and the velocity field at the eddy core depth; fourth panel: ITP drift track through the eddy showing dates and horizontal scale. From Zhao et al., (2016).

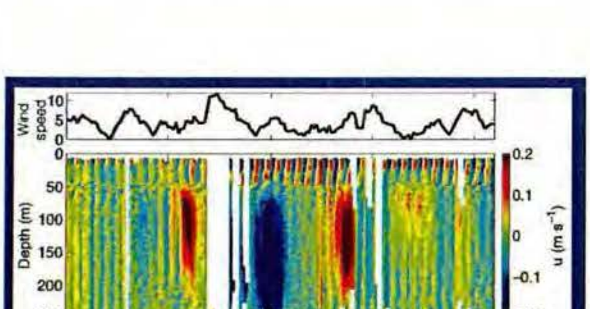
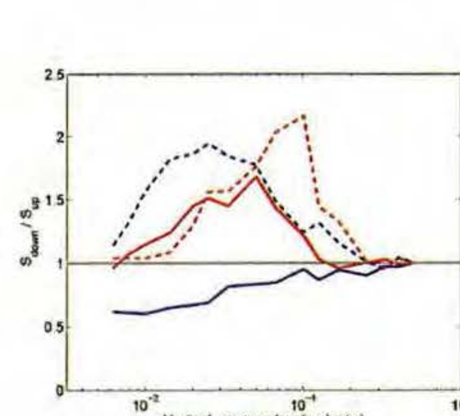


Figure 5: a 25-day segment of MIZ buoy observations showing wind speed (top) and the north-south component of ocean velocity (bottom). The banding, particularly evident after the wind event on 7/22, are near-inertial motions. The "blobs" of strong flow at 100-200 m depth are eddys bisected by the ITP-V drift track.

Figure 6: The ratio of downward to upward propagating internal wave energy over 70-250 m depth from MIZ clusters 2 (smoother ice; blue) and 4 (rougher ice; red) averaged over 15 March - 14 June (solid) and 15 June to 12 August (dashed).



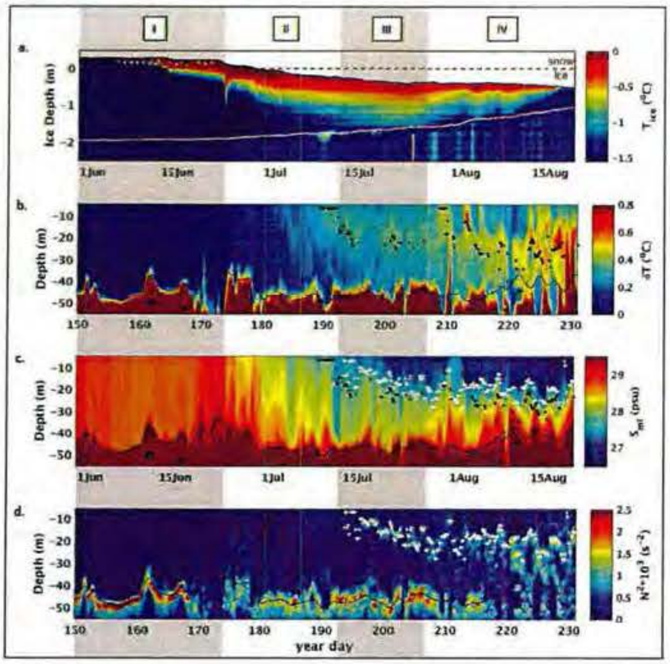


Figure 7: Overview of the ice-ocean boundary layer as observed by MIZ buoy cluster #2 during the MIZ study including (a) ice temperatures from an Ice-Mass-Balance instrument with top (black) and bottom (white) interfaces, (b) upper ocean departure from freezing (δT) and core of the Near-Surface Temperature Maximum (NSTM, black dots), (c) upper ocean salinity, depth of the summer halocline (white dots), and NSTM, and (d) upper ocean squared buoyancy frequency and summer halocline. Black line around 40 m represents the base of the winter pycnocline defined by the 1023.5 isopycnal. From Gallaher et al. (2016).

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